9.—Some petrological features of a spinel-bearing metagabbro in the pyroxene granulites of the Fraser Range, Western Australia

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Abstract

A preliminary study of a body of spinel-bearing metagabbro, 73½ miles east of Norseman, shows obvious textural, mineralogical and chemical differences between the fine-grained marginal facies and the coarse-grained central facies of the body. These differences may be of primary igneous origin or they may represent a response to later granulite facies metamorphism. Tectonic granulation possibly accounts for the absence of olivine in the marginal facies.

Variation of 2V within individual augite grains and the presence of haloes of andesine around spinel inclusions in labradorite suggest solid-state diffusion. Patchy concentration of volatile components appears to have controlled similar patchy development of clots of amphibole and carbonate. The presence of a titanium-rich amphibole (kaersutite) is a prominent mineralogical feature of the rocks.

Introduction

Several small low hills of well exposed metagabbros near the Eyre Highway 72 to 73 miles east of Norseman were mapped between the years 1952 and 1960. A description of the metamorphic phenomena exhibited by the spinel-bearing metagabbro is one of several projects which have been centred on a region known as the Allanite Pegmatite locality, 73½ miles from Norseman. A map of this region has been published in the paper recording the analytical data from the allanite pegmatite (Wilson, 1966) and here appears in modified form as Figure 1 of this paper.

The region is composed dominantly of basic pyroxene granulites, and metagabbro dykes. Many of the granulites are metavolcanic rocks. The allanite pegmatites which cut the granulites have not been metamorphosed. The "ages" of the pegmatites determined by K/Ar and Rb/Sr on Muscovite are 1210 x 10^6 years and 1280 x 10^6 years respectively. (Wilson, *et al.*, 1960, Table 1, No. 22). The true age is likely to be close to 1280 x 10^6 years.

Structure

The map shows two outcrops of metagabbro which have similar petrological features. The largest outcrop has been selected for detailed study. A specimen from this locality (Spec. 24522W) was briefly described in a reconnaissance study of parts of southern Western Australia. (Clarke, *et al.*, 1954, p. 40).

The metagabbro is now a lenticular body set in pyroxene granulites. The gabbro has been recrystallized more at the edges of the body than in the coarser central portions, so much so that it is not easy to delineate the original gabbro-granulite contact. The finer grained border facies of the gabbro has been converted to a pyroxene granulite. One of the purposes of the mineralogical study of one of these border granulites (Spec. 16307) is to see if there are distinctive features of the minerals which may aid in deciphering the several phases of igneous activity and metamorphism which have affected the region.

Structurally, the most obvious difference between the granulites intruded by the gabbro and the granulites formed by recrystallization of the margins of the gabbro is that the former show well developed tight shear folds and megascopically lineated pyroxenes, quartz and feldspar particles. The granulites formed from the gabbro, however, show no megascopic lineation, and are much more homogeneous than are the granulites thought to be derived from the basic volcanic rocks. In this locality the foliation of the granulites appears to be parallel to the primary structures of the metamorphosed volcanic rocks.

The lineation and fold-axes of the country rocks are coincident, and the map shows that the general structural trend is that of the whole Fraser Range (which extends about 14 miles westward to the Fraser "Fault"—Wilson, 1965). Plunges of minor fold-axes are steep in this region but are commonly shallow in the more rigidly aligned granulites further to the west.

Although the granulites formed from recrystallization of the gabbro show no obvious megascopic lineation it is likely that some deformation accompanied their metamorphism which was essentially a thermal metamorphism.

Petrography

Although petrographic study reveals a large variation in mineral proportions and grain size in the metagabbro, most of the boundaries are not obvious in the field. The metagabbro is mostly olivine-bearing, and ranges in composition from a meta-eucritic norite to a metanorite. Rhythmic banding is generally absent. However, a large irregular block of metagabbro was observed (Spec. 41856W) which has crude banding, with strike 15°, dip 65°E. Banding and grain size of this and related rocks is so coarse that it could scarcely have been developed within the present boundaries of such a narrow gabbroic body. This suggests that the metagabbro is a relic of a much larger, possibly, flat-lying body which has become broken up during a late phase of granulite metamorphism.

In this paper only the more normal rock types are described. These are illustrated by a series of specimens collected from the centre of the lenticular body (Spec. 16311) to its western contact (Spec. 16307) (see Fig. 1).

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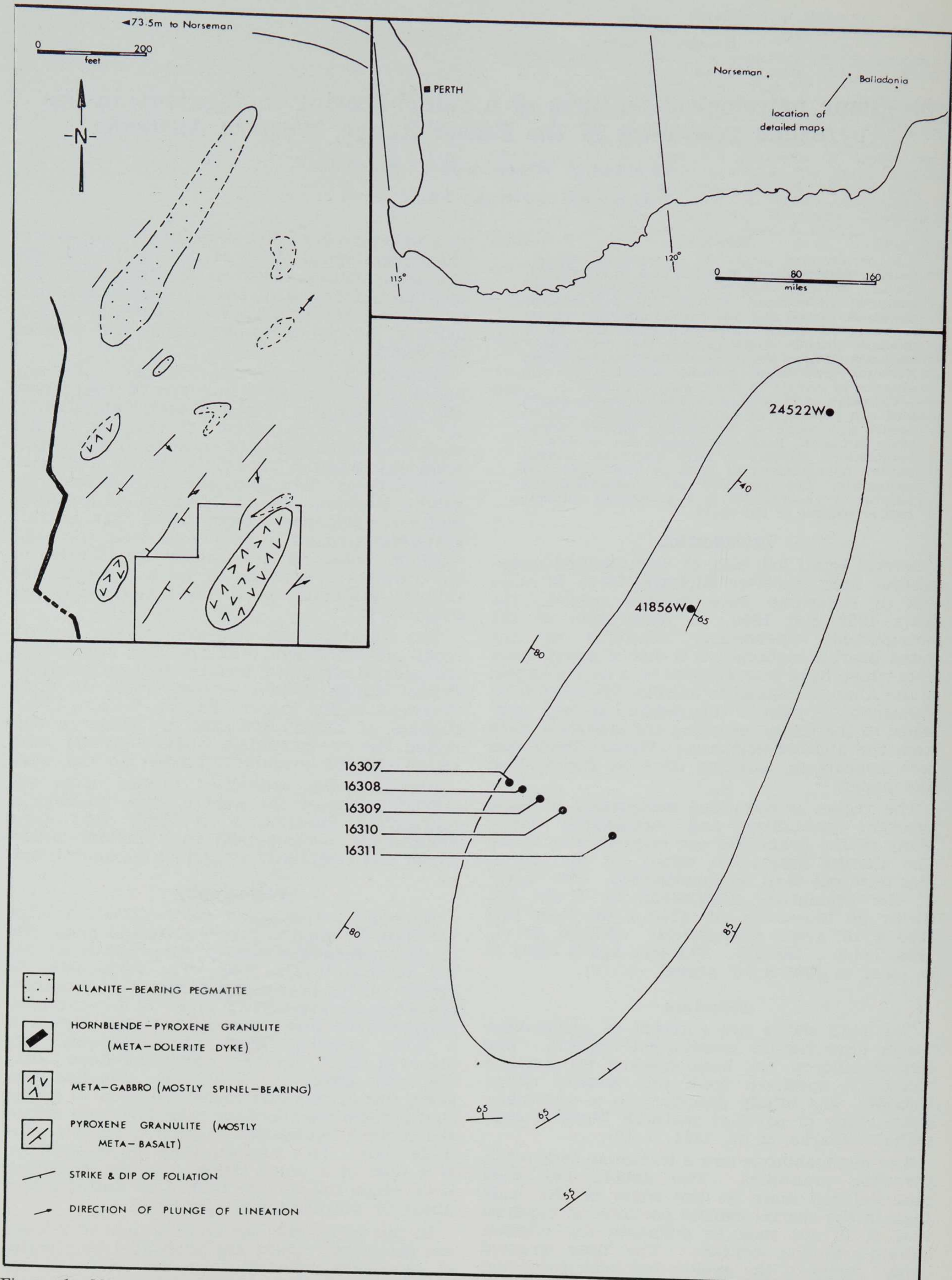

Figure 1.—Map showing the general geology and location of the spinel-bearing metagabbro body. The map on the lower right shows the position of specimens referred to in the text.

Coarse-grained spinel-bearing rocks

Spinel occurs principally in the coarse-grained central portion of the body, of which Spec. 16311 and 24522W are characteristic. Although partially recrystallized, the original gabbroic, subophitic texture with plagioclase partially enclosed by pyroxenes is still recognisable. Concentrations of mafic minerals are common.

Plagioclase (An_{52}) occurs as subhedral and anhedral grains, often elongate, up to 4 mm in length. A few grains, show normal zoning from An_{67} to An_{52}. Most grains show well developed albite twinning. However, although there is no evidence of deformation the twin lamellae of some grains are irregular or discontinuous. Most grains contain abundant inclusions of euhedral green spinel whose development has impoverished the adjacent host plagioclase in anorthite content. Thus the spinel grains are enclosed by haloes of andesine which vary in composition from An_{37} to An_{42}. (See Fig. 2.)

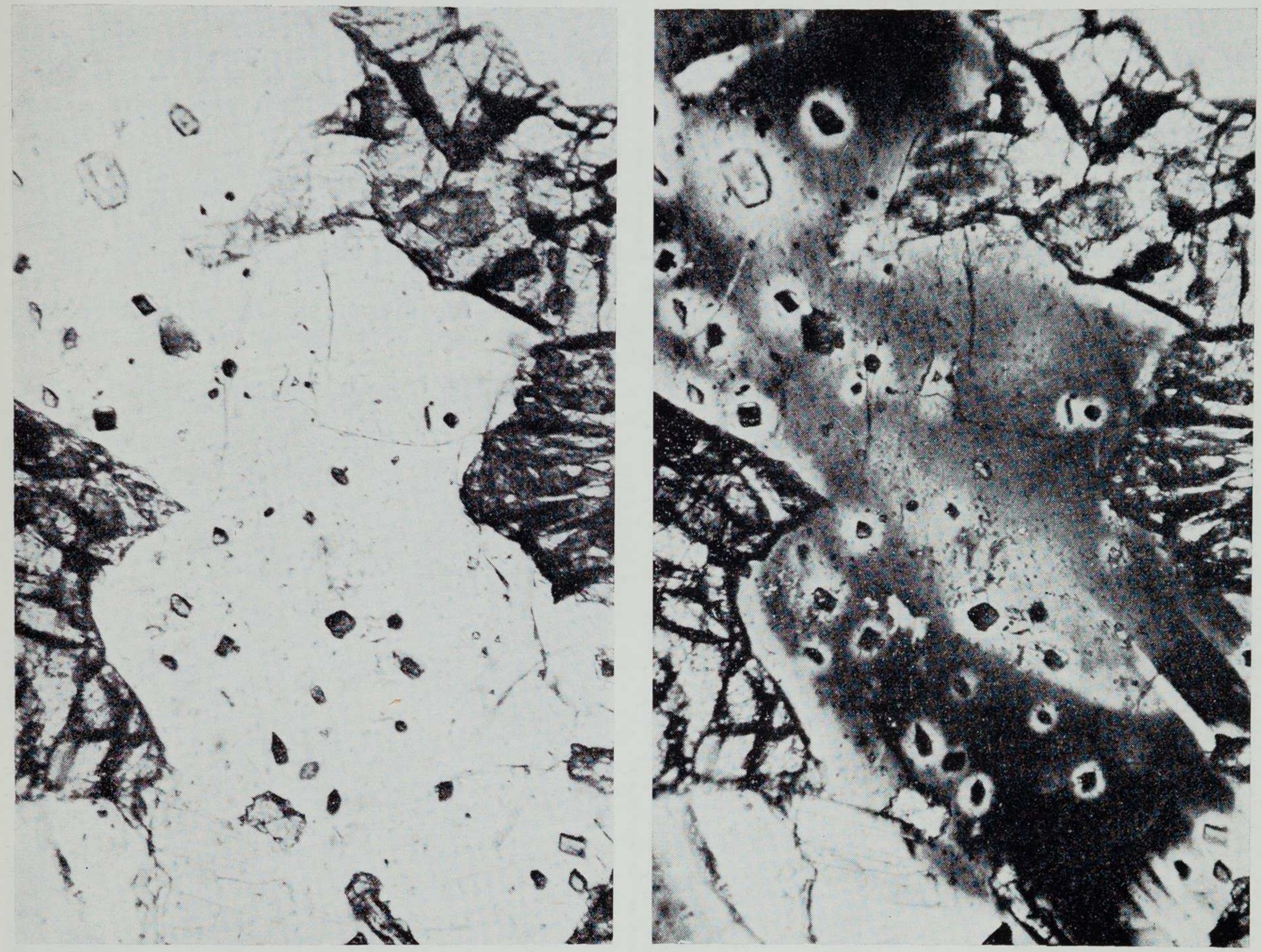

Figure 2.—A (left) Photomicrograph of a plagioclase grain (white) in Spec. 16311 showing euhedral spinel inclusions (shades of dark grey). The other dark mineral is clinopyroxene which contains some vermiform spinel inclusions. Plain light, X80. B (right).—Same field of view as Figure 2A with nicols crossed. Note the andesine haloes around spinel inclusions in the labradorite host.

Hypersthene occurs in two forms: (i) as anhedral grains (0.5 mm to 3.0 mm) which contain inclusions of spinel and olivine. Exsolution lamellae up to 0.04 mm in width are common. (ii) as small anhedral grains (up to 0.5 mm) which are devoid of exsolution lamellae. They form part of a granular aggregate of hypersthene, augite, spinel and olivine. Both forms are very faintly pleochroic and no compositional differences are apparent. In Spec. 16311, $\alpha = 1.713$, $2V/\gamma = 63°$; composition using γ is Fs37 (Deer, Howie & Zussman, 1962, 2: 28).

Augite occurs as anhedral grains (up to 4 mm) which commonly show patchy or undulose extinction. Exsolution lamellae are common. The augite, hypersthene, spinel and olivine commonly form granular aggregates which appear to pseudomorph an original gabbroic texture. A notable optical property of the augite is that variation in 2V demonstrates marked variation in composition within some augite grains. Figure 3 illustrates this phenomenon. In Spec. 16311, the normal value for $2V\gamma$ is 49° whereas it is about 57° near plagioclase and about 42° near olivine. $\beta = 1.700$. The composition approximates $Ca_{40}Mg_{36}Fe_{24}$ (Deer, Howie & Zussman, 1962, p. 132).

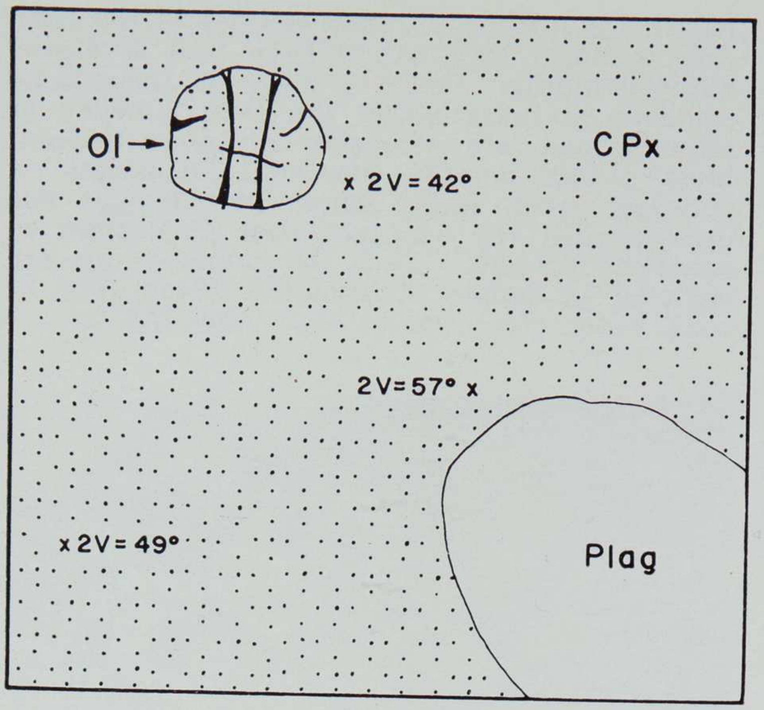

Figure 3.—Sketch illustrating solid-state diffusion in the coarse-grained facies of the metagabbro as shown by variation in $2V/\gamma$ measured within a single grain (CPx) in Spec. 16311. Near plagioclase (white), $2V = 57°$, whereas near the olivine grain (Ol) $2V = 42°$. The normal 2V is 49°. Approx. X50.

Amphibole. The presence of a strongly pleochroic titaniferous amphibole (a kaersutite—see Table 1 for analysis and optical data of kaersutite from 24522W) is one of the most prominent mineralogical features of the metagabbro. The pleochroism is X = pale yellow, Y = medium red-brown, Z = deep red-brown. The kaersutite forms aggregates of anhedral grains (up to 1.5 mm) which are commonly dispersed between the somewhat more fine-grained pyroxene-spinel-olivine aggregates.

Olivine (chrysolite—see analysis and optical data, Table 2) occurs as small anhedral grains (up to 0.5 mm) which may be included in the mafic minerals of the granular aggregates and in some of the larger plates of augite.

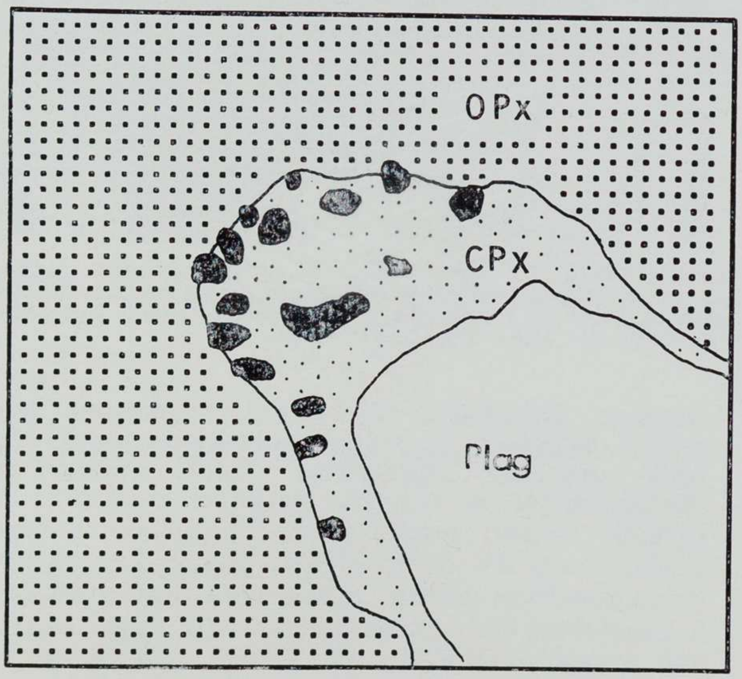

Figure 4.—Sketch showing a reaction texture in Spec. 16311. A granular aggregate of spinel (black) and augite (light stipple, CPx) is shown separating hypersthene (coarse stipple, OPx) and plagioclase (white). Approx. X50.

Spinel (pleonaste) occurs in two forms: (i) as stout euhedral crystals in plagioclase. The crystals commonly range in size from 0.02 mm to 0.04 mm (up to 0.1 mm), and are fairly evenly distributed throughout the host. However, in some instances there is a concentration of spinel crystals along some of the twin planes of the plagioclase.

(ii) As anhedral grains scattered throughout all of the mafic minerals. Spinel is uncommon in the centres of large hypersthene grains. However, it is commonly concentrated at the margins of these grains. In Figure 4 an aggregate of spinel and augite is shown separating hypersthene and plagioclase.n $= 1.776 \pm 0.003$, a= 8.140Å.

The accessory minerals, ilmenite, biotite, apatite and calcite are rare. The biotite is strongly pleochroic in red-browns and is commonly associated with amphibole as also is calcite.

Toward the margin of the metagabbro body the rocks are progressively more strongly re-

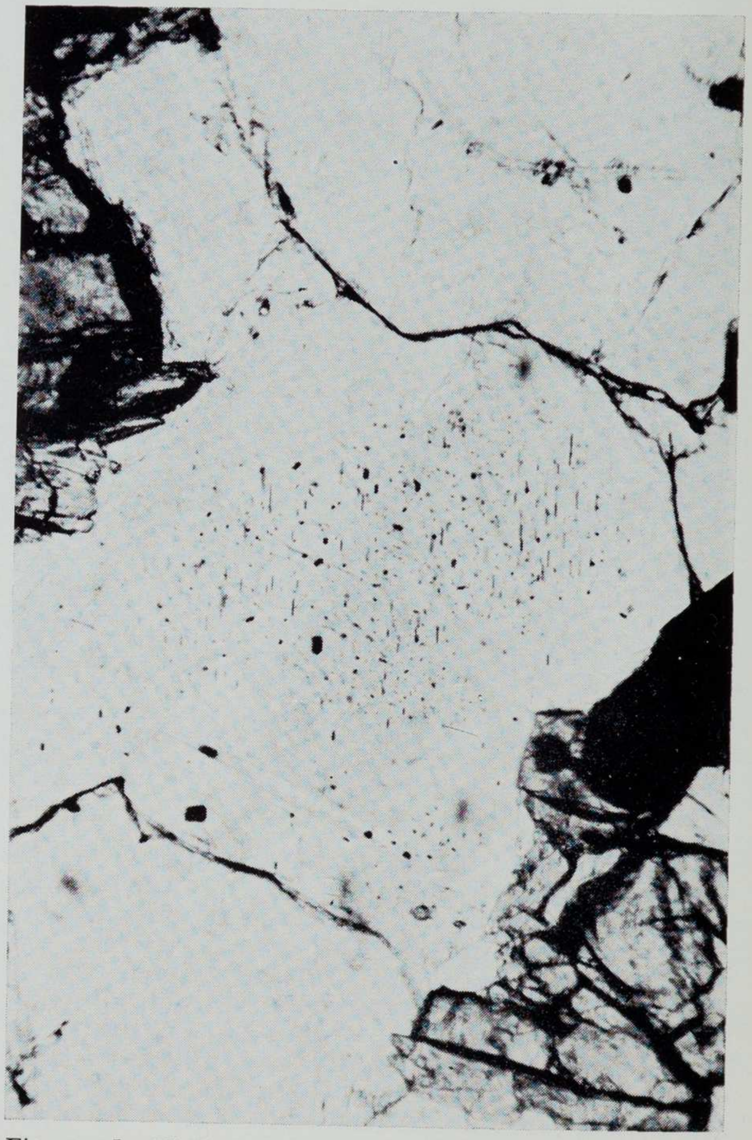

Figure 5.—Photomicrograph of Spec. 16307 showing minute rods of almost opaque spinel (black) included in plagioclase (pale grey). The other dark minerals are clinopyroxene (dark grey) and kaersutite (black). Plain light, X100.

crystallized. Although some elongate plagioclase grains occur in Specs. 16310, 16309 and 16308 a gabbroic texture is difficult to recognize. Toward the margin of the body plagioclase is recrystallized to form aggregates of polygonal grains. Spinel and olivine occur in the same manner as in Spec. 16311 but are progressively less plentiful. Olivine has been virtually eliminated in Spec. 16309.

Marginal facies

The marginal portion of the body is represented by Spec. 16307. This has been completely recrystallized to an aggregate of polygonal grains normally ranging in size from 0.5 mm to 1 mm.

Plagioclase forms well twinned grains (0.5 mm to 0.8 mm), and shows slight normal zoning which varies from An_{50} to An_{55}. The plagioclase contains only tiny spinel inclusions in contrast with that of the coarser rock, Spec. 16311. They occur as minute rods which are an average length of about 0.003 mm (Fig. 5).

Hypersthene occurs as anhedral grains and aggregates of grains up to 3 mm, averaging 0.5 mm. Fine exsolution lamellae are common. It is moderately pleochroic with X=pale pink, Y= pale yellow, Z=greenish-grey.

Amphibole, a strongly pleochroic titaniferous amphibole, is a prominent feature of both this rock and the coarse-grained rocks.

Augite is much more granular than in the coarse metagabbro, and is normally associated with granular hypersthene in aggregates. A chemical analysis shows it to be a calcic augite, $Ca_{44.4}$, $Mg_{37.2}$, $Fe_{18.4}$ (Table 3).

Mineralogy

Amphibole

The amphibole from Spec. 16307 and 24522W differs somewhat from the more normal brown hornblende of granulite facies rocks. Prider, (Clarke, *et al.*, 1954, p. 40) in describing the amphibole from Spec. 24522 noted its unusual pleochroic colours which are reminiscent of barkevikite. He pointed out that this is the only occurrence of this deep reddish-brown amphibole in the collection of Precambrian rocks from southern Western Australia.

TABLE 1

Amphibole analyses

	1	2	3	4	5	6	7
SiO_2	38.83	38.94	40.65	39.20	39.83	40.88	42.17
TiO_2	4.71	5.38	4.52	4.88	2.56	0.22	2.39
Al_2O_3	14.29	15.30	17.12	13.25	14.98	11.04	12.22
Fe_2O_3	3.66	2.02	4.26	2.97	7.66	7.56	3.28
FeO	10.43	9.98	5.53	10.49	3.78	17.41	14.42
MnO	0.00	0.00	0.34	0.17	....	1.32	0.17
MgO	10.22	10.52	9.96	11.57	14.44	5.92	9.42
CaO	12.22	12.66	12.88	12.59	12.39	10.46	11.46
Na_2O	1.84	1.89	1.74	2.68	2.27	3.75	1.51
K_2O	2.13	1.92	2.80	0.88	1.25	0.78	1.41
P_2O_5	0.07	0.05	....	....	....	....	0.06
H_2O+	1.57	1.62	0.36	1.17	0.58	1.16	1.50
H_2O-	....	....	....	0.02	....	....	....
F	0.21	0.23	....	0.00	....	....	0.17
	100.18	100.51	100.16	99.87	99.74	100.50	100.18
Less O = F	0.09	0.10	....	....	....	....	....
Total	100.09	100.41	100.16	99.87	99.74	100.50	100.18
			Numbers of ions on the basis of 24 (0,OH,F)				
Si	5.823	5.776	6.044	5.908	5.919	6.377	6.383
P	0.009 } 8.00	0.006 } 8.00	.... } 8.00	.... } 8.00	.... } 8.00	.... } 8.00	.... } 8.00
Al	2.169	2.218	1.956	2.092	2.081	1.623	1.617
Al	0.357	0.458	1.044	0.262	0.543	0.407	0.548
Ti	0.531	0.600	0.506	0.553	0.286	0.025	0.270
Fe^3	0.413 } 4.89	0.226 } 4.85	0.476 } 4.96	0.336 } 5.09	0.857 } 5.35	0.886 } 5.14	0.371 } 5.13
Mg	2.284	2.326	2.207	2.598	3.198	1.376	2.114
Fe^2	1.308	1.238	0.688	1.322	0.470	2.271	1.816
Mn	....	....	0.043	0.022	....	0.174	0.021
Na	0.535	0.544	0.502	0.782	0.654	1.134	0.439
Ca	1.963 } 2.91	2.012 } 2.92	2.051 } 3.08	2.033 } 2.98	1.972 } 2.86	1.748 } 3.04	1.850 } 2.56
K	0.407	0.364	0.530	0.168	0.238	0.156	0.269
OH	1.571 } 1.67	1.603 } 1.71	0.358 } 0.36	1.177 } 1.18	0.575 } 0.58	1.208 } 1.21	1.506 } 1.59
F	0.100	0.108	....	....	....	....	0.080
$\frac{100Mg}{Fe^{+2}+Fe^{+3}+Mg+Mn}$	57.0	61.4	64.6	60.7	70.6	29.2	46.6
α	1.673	1.675	....	1.681	1.667	1.691	1.670
γ	1.704	1.705	....	1.700	1.688	1.707	1.692
$2V/\alpha$	80°(est.)	80°(est.)	....	82°	....	....	....

1. Kaersutite, Spec. 16307, metagabbro, Fraser Range, Western Australia
2. Kaersutite, Spec. 24522W, metagabbro, Fraser Range, Western Australia
3. Kaersutite, hornblende monchiquite, Deer, Howie & Zussman, 1960, **2** : 322, no. 3
4. Kaersutite, melanocratic comptonite, Deer, Howie & Zussman, 1960, **2** : 322, no. 8
5. Basaltic hornblende, tephrite, Deer, Howie & Zussman, 1960, **2** : 317, no. 3
6. Barkevikite, nepheline syenite, Deer, Howie & Zussman, 1960, **2** : 329, no. 3
7. Average of ten analyses of brown hornblende from granulite facies rocks, Colton, New York. (Engel, *et al.*, 1964, Table 3, p. 138).

The amphibole is strongly pleochroic in shades of red-brown and has higher refractive indices than for common hornblende. The value of 0.5 to 0.6 atoms of Ti per formula unit is more than twice the normal maximum value for Ti in other amphiboles. The replacement of Si by Al of approximately 2 atoms per formula unit is more than twice the normal maximum value for Ti in other amphiboles. The replacement of Si by Al of approximately 2 atoms per formula unit is close to the theoretical limit and is greater than is usual in brown hornblendes of granulite facies rocks (see Table 1). The amphibole from the metagabbro also has higher alkalis than for common hornblende.

These features are characteristic of kaersutitic amphiboles. However, kaersutite cannot always be easily distinguished from barkevikite and basaltic hornblende in thin-section. Table 1 shows analyses of Spec. 16307 and 24522W compared with published kaersutite analyses together with an analysis of a basaltic hornblende and of a barkevikite.

Basaltic hornblende is characterized by a high Fe^{+3}/Fe^{+2} ratio, and low hydroxyl content. The Mg content is invariably higher than the total Fe, and in this respect basaltic hornblende shows marked contrast with kaersutite.

The main differences between barkevikite and kaersutite are the higher content of total Fe in barkevikite, and the high content of Ti in kaersutite. Barkevikite also has a smaller amount of Al, and may contain comparatively high Mn.

Strong similarities in the relative proportions of the major oxides in Spec. 16307 and 24522W and in the published kaersutite analyses are evident.

However, there are slight differences between Spec. 16307 and Spec. 24522W, notably in the proportions of Al in six-fold co-ordination (Al^{vi}), Ti, Fe^{+3}, Fe^{+2} and Mg. The variation may be explained in terms of the substitution relationship:

$$(Al^{vi}, Fe^{+3}, Ti) \longrightarrow (Mg, Fe^{+2})$$

Lower Fe^{+3} and Fe^{+2} in Spec. 24522W compared with Spec 16307 is compensated for by appropriate increase in Al^{vi}, Ti and Mg so that the sum of the atoms of Al^{vi}, Fe^{+3} and Ti and of Fe^{+2} and Mg are comparable for both amphiboles, as indicated below:

	16307	24522W
Al^{vi}	0.357	0.458
Ti	0.531	0.600
Fe^{+3}	0.413	0.226
	1.301	1.284
Mg	2.284	2.326
Fe^{+2}	1.308	1.238
	3.592	3.564

The reason for the variations cannot be readily explained, for the host rocks are similar in bulk composition (see Table 4). However it is evident that the minerals in Spec. 24522W do not represent an equilibrium assemblage, whereas those in Spec. 16307 have closely approached this condition. This fact provides a possible explanation for the variations discussed.

Pyroxenes

The co-existing pyroxenes from the recrystallized margin of the metagabbro (Spec. 16307; see Table 3 for analyses) do not appear to differ appreciably from co-existing pyroxenes of other granulite terranes. The proportions of the major oxides fall well within the known limits of composition of granulite facies pyroxenes. The distribution coefficient with respect to Mg-Fe (K_D—see Table 3) is 0.562 for the coexisting pyroxenes. This falls within the raneg of K_D observed for coexisting pyroxenes of normal granulites.

Due to the problems attendant on preparation and analysis of meaningful samples of exsolved pyroxenes, the pyroxenes from the central portion of the gabbroic body have not yet been analysed.

TABLE 2

Chemical analysis of olivine from metagabbro, Spec. 16311, Fraser Range

	Fraser Range 16311
SiO_2	38.80
TiO_2	....
Al_2O_3	0.46
Fe_2O_3	0.75
Cr_2O_3*	0.005
FeO	23.96
MnO	0.32
NiO*	0.065
MgO	35.26
CaO	0.29
Na_2O	tr.
K_2O	tr.
H_2O^+	....
H_2O^-	....
	99.91
Ions on basis of 4 oxygens	
Si	1.018
Al	0.014
Ti	....
Fe^{+3}	0.015
Cr	....
Mg	1.378
Ni	0.001
Fe^{+2}	0.526
Mn	0.007
Ca	0.008
γ	1.691
α	1.715
β	1.730
$2V/\alpha$ (est.)	85°

* Determined on optical spectrograph

Olivine

The analysis of the olivine from Spec. 16311 shows that it is an iron-rich chrysolite (Fa 27.6). Recalculation of an analysis of the whole rock (Spec. 16311) shows that the composition of the normative olivine is comparable (Fa 26). However the norm implies the presence of about 37% olivine in Spec. 16311, whereas it contains only about 8% in the mode. This discrepancy is probably due to the presence of amphibole in

TABLE 3

Analysis of co-existing clinopyroxene and orthopyroxene from metagabbro Spec. 16307, Fraser Range.

	1		2	
SiO_2	50.37		51.31	
TiO_2	0.89		<0.01	
Al_2O_3	4.39		1.29	
Fe_2O_3	3.20		1.17	
FeO	7.86		23.90	
MnO	0.05		0.26	
MgO	12.20		20.81	
CaO	20.27		0.74	
Na_2O	0.73		0.12	
K_2O	0.03		0.03	
P_2O_5	<0.01		0.06	
	99.99		99.69	
Ions on basis of 6 oxygens				
Si	1.881	2.00	1.942	2.00
P			0.002	
Al	0.119		0.056	
Al	0.074	1.98	0.002	2.01
Ti	0.025		....	
Fe^3	0.090		0.033	
Mg	0.679		1.174	
Fe^2	0.246		0.757	
Mn	0.002		0.008	
Ca	0.811		0.030	
Na	0.053		0.009	
K	0.001		0.001	
Mg	37.2		58.9	
Fe	18.4		39.6	
Ca	44.4		1.5	
β	1.700		1.713	
2V	+51°		—63°	
Kd*		0.562		

1. Clinopyroxene, Spec. 16307, metagabbro, Fraser Range, W.A.
2. Orthopyroxene, Spec. 16307, metagabbro, Fraser Range, W.A.

$$* \ Kd = \frac{\dfrac{Mg}{Fe^{+2}}\ OPx}{\dfrac{Mg}{Fe^{+2}}\ CPx}$$

the rock which is not taken into account in CIPW normative calculations. Moreover, in the recrystallized rock 16307 (which contains no olivine) the norm implies the presence of 12% olivine.

Spinel

This may occur in either one or both of the following forms (i) euhedral crystals in plagioclase; (ii) anhedral grains in aggregates of the mafic minerals. Optical and X-ray examination have not shown any difference in the composition of the two forms of spinel.

Discussion

There are obvious textural, mineralogical and chemical differences between the marginal and central portions of the metagabbro body see Table 4). These differences may be of primary igneous origin, or they may represent a response to later granulite facies metamorphism.

Textural features

The textural variations described above show that the coarse-grained facies of the centre has retained an essentially igneous texture. Nearer to the marginal facies the texture cannot be distinguished from that of surrounding granulites. We consider that this variation reflects an increasing degree of recrystallization of the gabbro in response to the thermal and mechanical effects of metamorphism. The recrystallization of the marginal facies would have been aided by an initial fine grain size, such as is normal in a chilled margin.

Significance of olivine in the metagabbro

Analyses show that all rocks in the metagabbro are undersaturated with respect to silica. The composition probably represents a close approximation to the gabbroic magma. The silica-undersaturation is reflected in the development of low silica mineral phases such as olivine, kaersutitic amphibole and spinel.

Olivine is absent however, from the marginal facies, even though chemical analysis of the rock shows that it could have been an important phase. A possible explanation is that recrystallization of the marginal facies involved a degree of tectonic granulation whereby olivine became an unstable component and was replaced by an amphibole with comparable low content of silica. Under these circumstances the presence of olivine in the central coarse-grained facies could indicate that this portion of the body has been unaffected by the tectonic granulation which may have accompanied metamorphism.

Presence of volatile components

Calcite appears to be concentrated in clots of granular amphibole within otherwise unrecrystallized gabbro. The retention of calcite as well as of the hydroxyl of amphibole during metamorphism is favoured by high temperature and relatively high confining pressure.

Under these conditions patchy concentration of volatile components appears to have controlled similar patchy development of clots of carbonate and amphibole. It is suspected that the patchy concentrations of volatile components in the metagabbro represent concentrations of end-phase material from the crystallization of the gabbro. During recrystallization of the gabbro these volatile-rich domains have enabled "wet metamorphic clots" to develop in these sites.

Solid-state-diffusion and reaction phenomena

There is evidence to suggest that considerable movement of chemical components has taken place in the solid state within the rocks of the coarse-grained facies.

Variation of 2V within individual augite grains in Spec. 16311 implies variation in their composition. The $2V\gamma$ of the augite is lower around included olivine grains (42°) and higher around included plagioclase (57°) than the normal value (49°) (see Fig. 3). This suggests a marked increase in the calcium content of the augite adjacent to plagioclase, and a corresponding decrease in calcium content adjacent to olivine thus confirming some metamorphic redistribution of calcium in the rock.

A further example of solid state diffusion is that spinel inclusions in labradorite are surrounded by "haloes" of andesine. The original Ca-rich plagioclase of the gabbro was converted to a more Na-rich variety during metamorphism, thus releasing aluminium. Aluminium has been fixed as spinel within the plagioclase grains by

TABLE 4

Chemical analyses, modes and norms of some Fraser Range metagabbros.

		16307	16309	16311 (a)	16311 (b)	24522W
SPECIFIC GRAVITY		3.03	3.08	3.12		3.10
MODAL%	Plag.	48	45	33	20	31
	OPx	23	24	31 (OPx + CPx)	56 (OPx + CPx)	42 (OPx + CPx)
	CPx	10	13			
	Hbe	17	16	22	9	18
	Olivine	nil	trace	7	9	3
	Spinel	trace	1	7	6	5
	Opaques	2	1	tr.	tr.	1
OXIDE%	SiO_2	49.23		45.88		48.03
	TiO_2	0.70		0.60		1.08
	Al_2O_3	14.63		10.51		14.56
	Fe_2O_3	2.49		2.37		1.76
	FeO	10.12		10.46		10.08
	MnO	tr.		tr.		0.24
	MgO	11.29		19.15		12.57
	CaO	8.85		7.50		9.04
	Na_2O	2.15		1.80		1.69
	K_2O	0.43		0.56		0.41
	P_2O_5	0.04		0.15		0.23
	H_2O^+	0.40		0.86		0.34
	H_2O^-	0.04		0.05		0.22
	Total	100.37		99.89		100.25
NORMATIVE%	Or	2.56		3.28		2.42
	Ab	18.20		15.21		14.30
	An	28.99		18.97		30.94
	Di Wo	6.12		7.18		5.18
	Di En	3.74		4.96		3.24
	Di Fs	2.05		1.64		1.63
	Hyp En	13.88		4.10		15.24
	Hyp Of	7.59		1.42		7.65
	Ol Fo	7.36		27.09		8.99
	Ol Fa	4.42		10.19		4.97
	Mag	3.61		3.43		2.55
	Il	1.34		1.14		2.05
	Ap	0.10		0.37		0.55

magnesium which has diffused through the plagioclase from nearby olivine. Once nucleated, spinel crystals appear to have continued to grow, thus producing prominent haloes of andesine around the spinel. The expelled calcium appears to have been used to produce augite or amphibole outside the plagioclase grains.

Concentration of spinel along some grain boundaries, particularly those separating plagioclase and hypersthene, has resulted from limited reaction between these two minerals to form spinel and clinopyroxene, as shown in Figure 4.

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